Review on Permeable Pavement Systems

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Abstract

The purpose of this review paper is to compact the wide range and spread the relevant works on permeable pavement systems, and also to deal with the current research and line of works to recommend the future areas of research work, also outlined about the important role of the permeable pavement systems in sustainable urban drainage systems in both the traditional and modern context, and discussed in brief about the permeable pavement systems, and also point up the detailed design in terms of structural and hydrological aspects of a type of permeable pavement systems. Particular emphasise is given for maintenance, water quality control aspects which includes the microbiological point of view of permeable pavement system and the pollutants. Recent research on the combined geothermal heating and cooling, water treatment and recycling pavement system is promising which are discussed in short. At last the future research and innovations are discussed in briefly.

The intent of this review is to provide stakeholders in storm water management with the critical information that is needed for the foster acceptance of permeable pavement systems as a viable alternative to the traditional systems.

Keywords: permeable pavement system, sustainable urban development system, geothermal heating and cooling system, recycling pavement system, porous pavement, storm water management

1. Sustainable Urban Drainage Systems (SUDS)

Sustainable Urban Drainage Systems has many other names like sustainable drainage schemes and sustainable drainage systems. Whatever: the key point is that it is sustainable drainage – a series of methods for dealing with drainage in a sustainable manner, using technologies that minimise the environmental impact of our lifestyles, buildings, structures and surfaces.

Sustainable Urban Drainage Systems challenge the traditional approach of wastewater treatment by optimising the resource utilisation and development of novel and more productive technologies.

In essence, SUDS applications seek to use the natural environment as a conduit for collected water, imitating what would happen if we pesky humans hadn't messed up everything with our buildings and pavements.

1.1. Advantages

There are numerous advantages by implementing Sustainable Urban Drainage Systems in our society but a few key pluses are mentioned below. Which are:

- Flood control and better management of storm water at source (source control)
- Pollution control
- Recharging of groundwater regimes and aquifers
- Reduced construction and maintenance costs
- Improved environment

1.2. Technologies of SUDS

There are dozens, if not hundreds of different SUDS applications, ranging from reed-bed treatment systems for polluted water, to settlement ponds for sediment, to simple swales and filter drains. Schemes are usually site-specific, taking a range of core technologies and using them either singly or in combination to create and
application that deals with the surface water drainage for a particular site.

One of such technology is Permeable Paving or Permeable Pavement Systems, but there is a subtle difference between these two which is permeable pavements allow water to pass through the paving structure, whereas suds-friendly pavements simply direct surface water to a suds installation such as a soakaway, a swale, etc.

The permeable pavement systems and SUDS are differentiated in the Figure. 1.

Suds-compliant pavements which can be defined as any pavement from which surface water is sent to a suds installation from where it may have the opportunity to drain to ground or be temporarily stored rather than being directly channelled into the public sewer system or an open watercourse.

1.3. Choosing of permeable pavement (or) SUDS

A Permeable Pavement is a SUDS-compliant pavement, but a SUDS-compliant pavement isn’t necessarily a permeable pavement. Consider a macadam driveway on which surface water is directed towards a linear channel which, in turn, is piped to a soakaway beneath the garden. That is a SUDS-compliant pavement, but couldn’t be classed as a permeable pavement.

Suds-compliant pavements always feature two key elements:
- How the water is collected and
- How it is then disposed

With concrete block permeable paving, the surface water is collected by passing through wider-than-usual joints between the individual block pavers and it is dispersed (usually) by means of a sub-pavement soakaway structure. Returning to the hypothetical suds-friendly macadam driveway, the surface water is collected by means of gradients on the macadam surface directing water into a collector channel. It is dispersed via a soakaway that may be some distance from the actual pavement surface. In short: it is possible to create suds pavements using any type of paving. It is not always necessary to use permeable paving, although these surfaces do offer a simple and effective option.

2. General

Permeable pavement systems are designed to achieve water quality and quantity benefits by allowing movement of storm water through the pavement surface and into a base/sub base reservoir, the water passes through the voids in the pavement materials (or) through the gap between pavers and provides the structural support as conventional pavement. That’s why permeable pavements can be served as an alternative to conventional road and parking lots. These pavements provides the ability to reduce urban runoff and also provide the opportunities to mitigate the impacts of urbanization on receiving water systems by providing at source treatment and management of storm water. Permeable pavement systems have been shown to improve the storm water quality by reducing the storm water temperature, pollutant concentrations and pollutant loading of suspended solids, heavy metals, polyaromatic hydrocarbons and some nutrients. Purposes for using permeable pavement systems instead of using other pavement systems are mentioned in the below section.

2.1. Purpose of permeable pavement system

1. Promote storm water infiltration, groundwater recharge, and stream base flow preservation
2. Reduce the discharge of storm water pollutants to surface waters
3. Reduce storm water discharge volumes and rates
4. Reduce the temperature of storm water discharges

2.2. Types of Permeable Pavement Systems

There are generally permeable varieties of asphalt, concrete, and interlocking pavers that means depending upon the type of materials used permeable pavement systems are divided into various types. Which are:
1. Permeable Asphalt (PA)
2. Permeable Concrete (PC)
3. Permeable Interlocking Concrete Pavements (PICP)
4. Concrete Grid Pavers (CGP)
5. Plastic Reinforcement Grid Pavers (PG)

2.2.1. Permeable Asphalt

Description
Permeable asphalt, also known as pervious, porous, "popcorn," or open-graded asphalt, is standard hot-mix asphalt with reduced sand or fines and allows water to drain through it. It generally consists of fine and coarse aggregate stone bound by a bituminous-based binder coarse. Porous asphalt over an aggregate storage bed will reduce storm water runoff volume, rate, and pollutants. The reduced fines leave stable air pockets in the asphalt. The interconnected void space allows storm water to flow through the asphalt as shown in Figure 2., and enter a crushed stone aggregate bedding layer and base that supports the asphalt while providing storage and runoff treatment. When properly constructed, porous asphalt is a durable and cost competitive alternative to conventional asphalt.

Porous asphalt can replace traditional impervious pavement for most pedestrian and vehicular applications. Open-graded asphalt has been used for decades as a friction course over impervious asphalt on highways to reduce noise, spray, and skidding. Porous asphalt performs well in pedestrian walkways, sidewalks, driveways, parking lots, and low-volume roadways. The environmental benefits from porous asphalt allow it to be incorporated into municipal green infrastructure and low impact development programs. The appearance of porous asphalt and conventional asphalt is very similar. The surface texture of porous asphalt is slightly rougher, providing more traction to vehicles and pedestrians.

2.2.3. Permeable concrete

Description

Permeable concrete, also known as pervious (or) porous concrete, gap-graded (or) enhanced porosity concrete, is concrete with reduced sand or fines and allows water to drain through it. Pervious concrete pavement is a unique and effective means to address important environmental issues and support green, sustainable growth. By capturing storm water and allowing it to seep into the ground, porous concrete is instrumental in recharging groundwater, reducing storm water runoff.

Pervious concrete is also known as no-fines or low fines concrete, pervious concrete is a mix of Portland cement, coarse aggregate, water and admixtures. Because there is little or no sand in the mix, the pore structure contains many voids that allow water and air to pass through. A typical pervious concrete pavement has a 15-25% void structure and allows 3-8 gallons of water per minute to pass through each square foot.

Carefully controlled amounts of water and cementitious materials are used to create a paste that forms a thick coating around aggregate particles without flowing off during mixing and placing. Using just enough paste to coat the particles maintains a system of interconnected voids.

The result is a very high permeability concrete that drains quickly. Due to the high void content, pervious concrete is also lightweight, 1600 to 1900 kg/m3 (100 to 120 lb. /ft3).

After placement or after paved, pervious concrete resembles popcorn as shown in Figure. 3. Its low paste content and low fine aggregate content make the mixture harsh, with a very low slump. The compressive strength of pervious concrete is limited since the void content is so high. However, compressive strengths of 3.5 to 27.5 MPa (500 psi to 4000 psi) are typical and sufficient for many applications such as:

- Parking lots
- Driveways
- Sidewalks/walkways
• Streets/road shoulders
• Other light traffic areas

Pervious concrete is a durable material; properly designed and constructed streets and parking lots will last many years with minimal maintenance. Thus concrete, conventional or pervious, is widely recognized as the lowest life cycle cost option available for pavement material selection.

Storm water runoff can send as much as 90% of the pollutants, such as oil and other hydrocarbon liquids found on the surface of traditional parking lots, directly into rivers and streams. By capturing rainfall and allowing it to percolate into the ground, soil chemistry and biology can treat the polluted water naturally. (Tennis, P.D., 2004[3])

Pervious concrete also contributes to enhanced air quality by lowering atmospheric heating through light colour and low density, decreasing the heat island effect which occurs with dark pavement surfaces. The heat island effect is characterized by an up to 4°C average temperature increase between an urban area and its surrounding countryside and an increase in the probability of smog due to the higher temperatures. (Gajda, J.W., Van Geem, M.G., 1997[4])

2.2.3. Permeable interlocking concrete pavement

Description

Permeable interlocking concrete pavement (PICP) consists of manufactured concrete units that reduce storm water runoff volume, rate, and pollutants. The impervious units are designed with small openings between permeable joints.

The openings typically comprise 5% to 15% of the paver surface area and are filled with highly permeable, small-sized aggregates. The joints allow storm water to enter a crushed stone aggregate bedding layer and "open-graded" base i.e., crushed stone layers with no small or fine particles. That supports the pavers while providing storage and runoff treatment. The void spaces among the crushed stones store water and infiltrate it back into the soil subgrade. The stones in the joints provide 100% surface permeability and the base filters storm water and reduces pollutants.

PICPs are highly attractive, durable, easily repaired, require low maintenance, and can withstand heavy vehicle loads.

Pervious concrete and porous asphalt rely on small-sized aggregates bound with asphalt or cement to create a porous matrix that supports vehicular traffic. In contrast, PICP relies on solid, high-strength concrete units to support traffic surrounded by small, highly pervious stone-filled joints to receive and infiltrate storm water. The stone-filled joints also contribute to interlocking and spreading wheel loads.

Depending on the paving unit design and pattern, PICP joints can vary between 1/8 and 1/2 in. (3 and 13 mm). Small-sized aggregate in the joints that allow water to pass through it can be somewhat deceptive. While PICP has less visible permeable surface area than porous asphalt or pervious concrete, PICP openings still provide high surface infiltration rates. These rates are well above practically all rainfall intensities, making their hydrological performance equal to or better than other permeable surfaces. The small aggregate in the joints and bedding also facilitates interlock and load transfer to neighbouring pavers. Unlike standard interlocking concrete pavement, no sand is used in PICP joints or bedding since it has very low permeability. The section is shown in the Figure 4.

Figure 4. Permeable interlocking concrete pavement section
The pavers are available in many different shapes and sizes. Paving surface can be of different types depending upon the type of pavers used. They are:
- interlocking shapes with openings,
- enlarged permeable joints, and
- Porous concrete.

ASTM C936 specifications (200 lb) state that the pavers can be of size 60 mm (2.36 in) thick with a compressive strength of 55 Mpa or greater. Typical installations consist of the pavers and gravel fill, a 38 to 76 mm (1.5–3.0 in) fine gravel bedding layer, and a gravel base storage layer is constructed.

PICP should not be confused with concrete grid pavements (i.e., concrete units with cells that typically contain topsoil and grass). Concrete grid pavement paving units can also infiltrate water, but at rates lower than PICP. Unlike PICP, concrete grid pavements are generally not designed with an open-graded, crushed stone base for water storage. Moreover, grids are for intermittently trafficked areas such as overflow parking areas and emergency fire lanes.

2.2.4. Concrete grid pavers

Description

Concrete grid pavements “green parking lots” provide a cool, green surface as shown in (Figure. 6.) Solution for vehicular access lanes, emergency access areas, and overflow parking areas, and even residential driveways.

Grids are proven contributors to reduced ambient urban temperatures thereby contributing to reduced heat island while taking in some rainfall and runoff.

Perforated concrete units as pavement were introduced when hollow concrete building blocks were placed in the ground to support cars.

The properties of concrete grid units are defined in ASTM C 1319, Standard Specification for Concrete Grid Paving Units (ASTM C, 1319-95[3]).

This specification defines concrete grids as having maximum dimensions of 24 in. long by 24 in. wide (610 mm by 610 mm) and a minimum nominal thickness of 31/8 in. (80 mm).

The minimum required thickness of the webs between the openings is 1 in. (25 mm). The percentage of open area ranges from 20 to 50 % and can contain topsoil and grass, sand, or aggregates in void spaces. A typical installation consists of grid pavers with fill media, 25 to 38 mm (1 – 1.5 in) of bedding sand, gravel base course, and a compacted soil subgrade (ICPI, 2004)

Dimensional tolerances should not differ from approved samples more than 1/8 in. (3.2 mm) for length, width, and height. The minimum compressive strength of the concrete grid units should average 5,000 psi (35 MPa) with no individual one less than 4,500 psi (31 Mpa). Concrete grid pavers range in weight from 45 lbs. (20 kg) to 90 lbs. (40 kg).

Concrete grid unit designs fall into two categories:
- Lattice, and
- Castellated as shown in Figure. 7.

2.2.5. Plastic Reinforcement Grid Pavers

Description

Lattice pavers have a flat surface that forms a continuous pattern of concrete when installed. Castellated grids include protruding concrete knobs on the surface making the grass appear continuous when installed.
for infiltration through large gaps filled with gravel or topsoil planted with turf grass. A sand bedding layer and gravel base-course are often added to increase infiltration and storage. The empty grids are typically 90 to 98 percent open space, so void space depends on the fill media (Ferguson, 2005[6]). To date, no uniform standards exist; however, one product specification defines the typical load-bearing capacity of empty grids at approximately 13.8 MPa (2,000 psi). This value increases up to 38 MPa (5,500 psi) when filled with various materials (Invisible Structures, 2001[7]).

Figure 8. Plastic reinforcement grid pavers

Generally the grid need to be installed onto a geogrid or geotextile covered by a layer of gravel bedding. The grids pavers can be filled with soil and grassed as the octagonal honeycomb cell structure as shown in the Figure 8. and open base promotes unrestricted root growth, or can be filled with gravel giving a high quality decorative look. The hexagonal cell structure will retain the gravel and prevent loss or gravel displacement.

The paving grids are ideal for driveways and for gravel or grass car parks. The paving system is the perfect solution for car parking for on grass that constantly becomes worn, muddy (or) rutted. Perfect for Grass car parks, lawn reinforcement, farm gateway entrances, grass roads, grass access routes and golf buggy paths.

The main types of concrete pavements are discussed above in brief context, other than those porous turf, resin bound permeable pavement, permeable clay brick pavements, bound recycled glass porous pavement are other types of permeable pavements.

2.3. Applications and Challenges

Permeable pavement systems (PPS) are suitable for a wide variety of residential, commercial and industrial applications, yet are confined to light duty and infrequent usage, even though the capabilities of these systems allow for a much wider range of usage. Where there is any concern about the possible migration of pollutants into the groundwater, PPS should be constructed with an impermeable membrane, and the treated storm water should subsequently be discharged into a Suitable drainage system, however this is discussed in the upcoming sections.

Common Applications of PPS are as follows:

- Vehicular access: residential driveways, service and access driveways, roadway shoulders, crossovers, fire lanes and utility access;
- Slope stabilisation and erosion control;
- Golf courses (cart paths and parking);
- Parking (church, employee, overflow and event);
- Pedestrian access; bicycle and equestrian trails; and land irrigation.

2.4. Sectional view of permeable pavement

Nearly all the types of permeable pavements has similar structure, the difference is in the surfacing layer. As we know the pavement system is a layer technology composing of various types of layers and each layer has its specific use. Different types of layer’s are mentioned below:

1. Surfacing course
2. Base course (bedding course)
3. Subbase course
4. Geotextile (optional)
5. Subgrade

Figure 9. Typical cross section of pavement

Figure 10. Cross section of permeable pavement
2.4.1. Surfacing course

This layer the topmost layer that the drivers and users see, generally it is identified by the type of pavement used. The surfacing course can be made up of materials like:

- Concrete blocks - now referred to as CBPP (Concrete Block Permeable Paving)
- Clay pavers
- Permeable macadam
- Permeable resin bound aggregate
- Gravel
- Grass pavers/cell matrix Ground Reinforcement
- No-fines concrete

2.4.2. Base course (bedding layer)

Generally the base course is also called as bedding layer which is again divided into two layers, out of which one is bedding course and the other is bedding reservoir. Base material (typically open graded gravel or drain rock). Surfacing course described above is constructed over a base course that doubles as a reservoir for the storm water before it infiltrates into the subsoil. The reservoir should consist of uniformly-sized crushed stone, with a depth sufficient to store all of the rainfall from the design storm. The bottom of the stone reservoir should be completely flat so that infiltrated runoff will be able to infiltrate through the entire surface. An open-graded base of crushed stone, which has 35 to 45 percent pore space, is installed below the surface pavement. The recommended base thickness is 6 inches for pedestrian use and 10 inches for driveways to provide adequate structural strength.

If sub drain is provided in the subbase then outlet elevation is a minimum of 3 inches above the bottom of the base course.

2.4.3. Subbase course

This is the load-bearing layer of the pavement. Typically constructed from crushed and graded stone. Essential beneath pavements subject to vehicular traffic, it may be omitted in certain other applications. In permeable pavement we should use highly permeable sub-base material. There's not much point in having a leaky surface layer if what's underneath just blocks or impedes the escape of the collected surface water. The ideal sub-base for such a scenario would need to provide strength and load-bearing capability along with practically zero-ability to hold water.

In conventional unbound sub-bases, the essential strength and load bearing capability comes from the carefully designed blend of fines and larger pieces creating an intense interlock, but the presence of all those fines would impede the flow of water through the material. So, there was a need to design an unbound material with no fines yet a high degree of interlock. The secret to this lies in the meticulous choice of particle sizes and angularity.

It is also made up of open graded materials, underdrain is present in the subbase reservoir at a depth of 3 inches from the bottom of the base course.

2.4.4. Geotextiles

Geotextiles are permeable fabrics which, when used in association with soil, have the ability to separate, filter, reinforce, protect, or drain. Geotextiles are typically made from polypropylene or polyester. Geo-textiles are three types woven, non-woven or knitted. Geotextiles are permeable sheets, usually, but not exclusively, non-biodegradable materials. In case of permeable pavement systems geotextiles act as permeable sheets and also to strengthen the soil at the tension surface.

In a permeable bituminous-stabilized base course, the presence of geotextile helps to reduce the rutting depth and rate of block breakage, maintaining a good level of pavement serviceability such as easy cleaning. A geotextile with a fibre area weight of 60gm/m^2 is usually applied. Furthermore, most geotextiles can help to retain and degrade oil, if clogging (e.g. silting) is not a problem.

2.4.5. Subgrade

The sub-grade layer of a pavement is, essentially, the underlying ground. It is also known as the "Formation Level", which can be defined as the level at which excavation ceases and construction starts; it's the lowest point of the pavement structure. Subgrade should be uniform and should be compacted such that it is minimum required for structural stability.

3. Design of permeable pavement systems

We are going to discuss the design of permeable pavement system under two aspects. Which are:

- Structural
- Hydrological

If permeable pavement will be used in a parking lot or other setting that involves vehicles, the pavement surface must be able to support the maximum anticipated traffic load. The structural design process will vary according to the type of pavement selected, and the manufacturer’s specific recommendations should be consulted. The thickness of the permeable pavement and reservoir layer must be sized to support structural loads and to temporarily store the design storm volume (e.g., the water quality, channel protection, and/or flood control volumes). On most new development and redevelopment sites, the structural support requirements will dictate the depth of the underlying stone reservoir.
The structural design of permeable pavements involves consideration of four main site elements:

- Total traffic
- In-situ soil strength
- Environmental elements
- Bedding and reservoir layer design

But here we are pointing up on the detailed design of permeable interlocking concrete pavement as it is used much in now a days and in short about porous asphalt and concrete pavements, as it is a review paper we cannot discuss in detail about the design of different types of permeable pavements.

3.1. Introduction

Figure 11. Schematic of the analysis process

If we properly design and construct a permeable pavement, they can help rainwater to infiltrate into the soil, decrease urban heating, replenish groundwater and reduce storm water runoff. Permeable pavements provide a different approach. Rather than channelizing precipitation along the surface of the pavement, the water is allowed to infiltrate and flow through the pavement surface where it can be stored and slowly allowed to return into the local groundwater system.

3.2. Design process

The design process for permeable pavements includes consideration of structural capacity to ensure that the pavement materials and thickness is sufficient to withstand the anticipated traffic loadings and a hydrological analysis to determine if the pavement system can accommodate the water infiltration for the selected design conditions and storm event. The overall design analysis as a flow is shown in the Figure 6.

3.3. Design inputs

For designing a pavement first we need to give some inputs to the pavement then only as a whole permeable pavement is designed as an output. There are various design parameters or inputs which are discussed in brief

3.3.1. Geometry

The permeable pavement geometry is needed to provide information on the configuration of the pavement structure. Specifically it is used to provide details on the dimensions of the pavement surface, pavement slope, and neighbouring catchment areas. The pavement geometry outlines the size, shape, and behaviour of pavement surface. This information is used to help estimate the volume of rainfall as well as the amount of water storage available.

3.3.2. Subgrade Layer

The subgrade material is the soil that is present below the pavement structure. This layer is important to understand in order to ensure that the pavement structure built protects the subgrade materials from damage. The drainage is also heavily impacted by the subgrade materials because a substantial quantity of the low yield storm events are typically dissipated through the subgrade materials into groundwater recharge.

3.3.3. Resilient Modulus

The subgrade material is important to understand because it often has the most variability. Since it is native material and, realistically, the only material that cannot be modified, the thickness of the other materials are designed around the subgrade strength. In order to evaluate the subgrade strength, a geotechnical parameter known as the resilient modulus is used.

3.3.4. Porosity

The porosity of a granular material represents the amount of voids in any volume of the material. Information on the density of the compacted material including the voids and the density of the granular particles are used to calculate the proportion of the volume available to store water. The porosity information is also used to estimate the speed that water can move through the granular material.

3.3.5. Granular Layer

The granular layers are the placed layers that are constructed above the subgrade material in order to provide structural strength and a smooth construction platform for the PICP. In permeable pavement systems, these layers are typically composed of granular materials that provide high levels of porosity to accept, store, and transport water to any outlets.
The placed granular layers are typically composed of one or two layers of aggregates known as base and subbase as shown in the figure Figure. 12. In a two layer system, a subbase is placed below the base to provide a low cost material that will contain most of the water in the system, while the base provides additional structural strength to prevent deformation at the surface of the subbase. In a one layer system, the material is just referred to as the base and it provides the structural support and water storage.

![Figure 12. Granular layer in PICP](image)

### 3.3.6. Paving Layer

The paving layer represents the layer of the bedding material (typically stone chip) and the pavers as shown in the Figure. 13. This layer provides a safe and durable surface for the traffic to drive on. The stiff surface and firm support of the bedding material helps to properly distribute the traffic loads over the granular materials.

![Figure 13. Paving layer in permeable PICP](image)

### 3.4. Structural Design

The structural design is very important in the design of pavement structures. Providing the correct layer thickness will ensure that lower layers are adequately protected which will ensure a long lasting pavement. The structural design is based on several important parameters including the placed materials, the expected traffic loading, the minimum acceptable level of serviceability, and the thickness of the placed layers.

The parameters required for the designing are discussed below in brief.

#### 3.4.1. Traffic

The traffic loading is a critical component of the structural design. This represents the types of loads that the pavement is expected to endure and support over its service life. The traffic information used as an input to the design procedure in terms of the Equivalent Single Axle Loads (ESALs) that the pavement is able to carry during its design life. The number of ESALs represents the damage caused by an equivalent number of 80 KN axles driving on the pavement. To estimate the total number of ESALs expected over the life of the pavement, the number and types of vehicles driving on the road need to be examined. The types of vehicle driving on the road have different characteristics, number of axles, and typical vehicle weights.

#### 3.4.2. Design Parameters

The structural design procedure for pavements has many variables. The design parameters are used to describe the condition of the roadway over the life of the pavement. The design parameters are divided into two main components representing the acceptable level of serviceability and the reliability of the design.

##### 3.4.2.1. Structural Base Thickness

The structural base thickness calculation summarizes the structural components and produces the recommended thickness of the granular materials to provide adequate structural capacity for the pavement.

##### 3.4.2.2. Precipitation

For the safety reasons, it is very important to prevent standing water on the surface of the pavement. Standing water can cause hydroplaning of vehicles, inconvenience for pedestrians, and potential flooding of neighbouring areas.

Thus, the expected precipitation is a critical factor when designing a permeable pavement system. The pavement system must be designed to allow as much of the overland flow into the system as possible. The pavement must then store and discharge the water into the groundwater and/or storm drain system.

##### 3.4.2.3. Storm Pattern

The storm pattern represents the change in rainfall throughout a storm event. The different types of storms represent whether the rain falls relatively evenly over a 24 hour period or if the majority of the rain occurs over a short duration. The type of storm is very dependent on the location of rainfall.

##### 3.4.2.4. Rainfall

The rainfall intensity is very dependent on the location of the site. The rainfall intensity is also typically provided for a range of storm events. The storm events represent...
the maximum rainfall expected over a 24 hour time period over a certain time period. For example, a 100 year storm represents the maximum rainfall intensity anticipated for any 1 day storm every 100 years. The longer the time period, the more extreme the storm is expected to be.

3.4.2.5. Inflow

Inflow summarizes the expected flow of water into the pavement system. The inflow is composed of rainfall onto the pavement surface as well as onto any previously specified catchment areas. This rate is then used to estimate how much water will accumulate in the base material as well as how long it will take to drain a fully saturated pavement section.

For every designing process analysis is required and it is discussed below in short.

3.4.2.6. Hydrology and hydraulics

Tests have shown that evaporation, drainage and retention within the permeable structures were mainly influenced by the particle size distribution of the bedding material, and by the retention of water in the surface blocks (Andersen et al., 1999 and Scholz, 2006).

Movement of water through the porous pavement installation is controlled by surface runoff, infiltration through the pavement stones, percolation through the unsaturated zone, lateral drainage at the base and deep percolation through the sub-grade. There are three possible fates for precipitation reaching the surface of a PPS installation (Scholz, 2006 and James and von Langsdorf, 2003): (a) infiltration to the base material where water that leaves the bottom or sides of the permeable pavement and enters the soil. Water infiltrates from the pavement base layer. It infiltrates the surrounding soil; (b) evaporation where water stored in puddles on an impermeable surface or temporarily trapped near the surface of permeable pavement will eventually evaporate to the atmosphere. If plants aid in the release of water to the atmosphere, as some permeable pavements are designed to be vegetated this process is termed evapotranspiration; and (c) runoff (overland flow) where amount of water leaving the surface of the pavement. This water enters the storm sewer network.

In designing a permeable pavement installation, it is fundamentally important to provide and maintain surface infiltration and storage capacity to allow an adequate volume of storm water to be captured and treated by the facility. In comparison to conventional asphalts, permeable and porous pavements provide more effective peak flow reductions (up to 42%) and longer discharging times. Abbot and Comino-Mateos, 2003 and Pagotto et al., (2000) said that there is also a significant reduction of evaporation and surface water splashing.

3.5. Structural and Hydrological analysis

The design of porous pavements can be somewhat complicated due to the interaction of the hydrologic properties and the structural properties of the pavement structure. The many properties of the layers, the materials, and the site layout can dramatically change the design life of a pavement.

The analysis to design the necessary pavement structure is divided into the two main components:

- Structural analysis
- Hydrological analysis

3.5.1. PICP Structural analysis

The key component of the structural design of a pavement is to ensure that the pavement surface reduces the stresses and strain at subsequent layers to prevent any significant plastic deformations. The structural analysis procedure accounts for the traffic loads and the structural capacity of the various layers in the pavement system. To assess the structural capacity of PICP, AASHTO empirical design equation to develop base thicknesses for supporting vehicular traffic. This design method relies on inputs such as traffic information, soils and pavement material information, reliability and serviceability levels. AASHTO empirical design method calculates a structural number (SN) which is the sum of layer coefficients, a dimensionless characterization of the stiffness of each pavement layer.

To determine the thickness of the required pavement layers, layer coefficients (default values or those assigned by the user) determine if the open-graded base types and thicknesses meet the design structural number or design SN. While the user can change default values, the program assumes that layer coefficients for open-graded bases are lower than those associated with dense-graded bases used under conventional impervious pavements.
The PICP paving layer thickness is consistently specified at 3 1/8 in. (80 mm) for the pavers plus 2 in. (50 mm) for the bedding layer. While a conservative default value of 0.3 per inch layer coefficient is assumed for the pavers and bedding layer, the user can nominate a paver-specific layer coefficient should it be available. Since the paving layer thickness is constant and its stiffness is characterized by this layer coefficient, only the open-graded base (usually the ASTM No. 57 stone held constant at 4 in. or 100 mm thickness) and the subbase thickness (ASTM No. 2 stone layer) requires designing. The subbase thickness is rounded up to the nearest inch (25 mm) to ensure a reasonable and conservative value for constructability. The software program applies to PICP subject to axle loads up to 24,250 lbs (11,000 kg) or a maximum vehicle load of 50,000 lb (22,680 kg) trafficked up to 1 million 80 kN (18-kip) equivalent single axle loads (ESALs). Users are cautioned when the design load exceeds 600,000 ESALs.

3.5.2. PICP hydrological analysis

The hydrological analysis is used to assess if the rainfall can be stored and released by the pavement structure provided. (Figure 8.) summarizes the hydrological modelling process. The hydrological analysis determines if the volume of water from user-selected rainfall events can be stored, infiltrated and released by the pavement structure. All water is modelled as a water balance using small time steps to characterize water inflow from precipitation into the PICP surface and runoff contributed from adjacent areas. Besides characterizing contributing runoff from adjacent areas, the user can elect to include perforated drain pipes in the base to accommodate outflow in low infiltration soils. These can be modelled at the bottom of the subbase or raised within it to create some detention.

The program also calculates the curve number and runoff coefficient for user selected rainfall events for the site.

Outflow is also estimated by calculating infiltrated water flowing directly into the PICP and from contributing areas, as well as drainage from the base into the soil or to drainage pipes during each time step. The combined process continually estimates the water level in the base and the amount draining from the PICP, during and after the storm. Output includes hydrographs for the rainfall, inflow from contributing areas, infiltration and outflow through drain pipes if required. Output variables can be set for water storage and harvesting if needed.

3.5.3. Porous asphalt structural design

Porous pavement thickness design is addressed in industry literature. Table 1 indicates thicknesses for porous asphalt design (NAPA 2008). This is excerpted from the National Asphalt Pavement Association porous asphalt manual which does not quantify maximum traffic loading.

Table 1 Minimum compacted porous asphalt thicknesses

<table>
<thead>
<tr>
<th>Traffic Loading</th>
<th>Minimum Compacted Thickness, in. (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Parking – Light or no trucks</td>
<td>2.5 (65)</td>
</tr>
<tr>
<td>Residential street – Some trucks</td>
<td>4.0 (100)</td>
</tr>
<tr>
<td>Heavy Trucks</td>
<td>6.1 (150)</td>
</tr>
</tbody>
</table>

Regarding AASHTO layer coefficients per inch (25 mm) of pavement layer thickness for porous asphalt, NAPA (2008) recommends the following in Table 2.

Table 2 AASHTO layer coefficients for porous asphalt, treated base and open-graded base

<table>
<thead>
<tr>
<th>Material</th>
<th>Layer Coefficient (per in.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Porous Asphalt</td>
<td>0.40 – 0.42</td>
</tr>
<tr>
<td>Asphalt-treated permeable base</td>
<td>0.30 – 0.35</td>
</tr>
<tr>
<td>Porous aggregate (open-graded) base</td>
<td>0.10 – 0.14</td>
</tr>
</tbody>
</table>

3.5.4. Pervious concrete pavement structural design

The National Concrete Ready Mix Association manual, Hydrologic Design of Pervious Concrete (2007 Leming) provides a methodology that utilizes the Natural Resource Conservation Service (NRCS) Curve Number method. The manual reviews software for hydrological calculations. While the software program does not include structural design, some recommendations are provided as charts in the appendix. Depending on axle loads, pavement thickness charts recommend 4, 6 and 8 in. (100, 150 and 200 mm) thick pervious concrete on soils with infiltration rates no lower than 0.1 in./hr (0.3 cm/hr). Quality.

There is no design guidance on the thickness of open-graded base required for traffic load support. The user is directed to consulting a design professional (e.g. civil engineer) for determining pervious concrete and...
base thicknesses on soils less than 0.1 in./hr (0.3 cm/hr) infiltration rate. Table 3 below replicates the pavement thickness information by Leming. The right hand column is added by the author to demonstrate the ESAL ranges supported by the various pervious concrete pavement thicknesses. The design charts note that a design professional should be consulted for lifetime designs greater than 720,000 ESALs.

3.6. Permeable pavement design criteria

3.6.1. Type of Surface Pavement

The type of pavement should be selected based on a review of the pavement specifications and properties and designed according to the product manufacturer’s recommendations.

3.6.2. Pavement Bottom Slope.

For unlined designs, the bottom slope of a permeable pavement installation should be as flat as possible (i.e., 0 percent longitudinal and lateral slopes) to enable even distribution and infiltration of storm water. On sloped sites, internal check dams or berms, as shown in the Figure. 16, Below, can be incorporated into the subsurface to encourage infiltration. In this type of design, the depth of the infiltration sump would be the depth behind the check dams. The depth and spacing of the barriers is dependent upon the underlying slope and the infiltration rate, as any water retained by the flow barriers must infiltrate within 48 hours. If an underdrain will be used in conjunction with the flow barriers, it can be installed over the top of the barriers, or parallel to the barriers with an underdrain in each cell.

![Figure 16. Use of flow barriers to encourage infiltration on sloped sites.](image)

3.6.3. Internal Geometry and Drawdown

- Rapid drawdown

Permeable pavement must be designed so that the target storage volume is detained in the reservoir for as long as possible—36 to 48 hours—before completely discharging through an underdrain. A minimum orifice size of 1 inch is recommended regardless of the calculated drawdown time.

- Infiltration Sump.

To promote greater retention for permeable pavement located on marginal soils, an infiltration sump can be installed to create a storage layer below the underdrain invert. This design configuration is discussed further below.

- Conservative Infiltration Rates.

Designers must use 1/2 of the measured infiltration rate during design to approximate long-term infiltration rates (for example, if the measured infiltration rate is 0.7 inches

3.6.4. Reservoir Layer

The reservoir layer consists of the stone underneath the pavement section and above the bottom filter layer or underlying soils, including the optional infiltration sump. The total thickness of the reservoir layer is determined by runoff storage needs, the infiltration rate of in situ soils, structural requirements of the pavement sub-base, depth to water table and bedrock, and frost depth conditions. A geotechnical engineer should be consulted regarding the suitability of the soil subgrade.

- The reservoir below the permeable pavement surface should be composed of clean, double-washed stone aggregate and sized for both the storm event to be treated and the structural requirements of the expected traffic loading (additional chamber structures may also be used to create larger storage volumes).
- The storage layer may consist of clean, double-washed stones of specific types because it provides additional structural stability.
- The bottom of the reservoir layer should be completely flat so that runoff will be able to infiltrate evenly through the entire surface. The use of terracing and check dams is permissible.

3.6.5. Underdrains.

Most permeable pavement designs will require an underdrain. Underdrains can also be used to keep detained storm water from flooding permeable pavement during extreme events. Multiple underdrains are
necessary for permeable pavement wider than 40 feet, and each underdrain must be located 20 feet or less from the next pipe or the edge of the permeable pavement. (For long and narrow applications, a single underdrain running the length of the permeable pavement is sufficient.) The underdrain should be perforated schedule 40 PVC pipe (corrugated HDPE may be used for smaller load-bearing applications), with 3/8-inch perforations at 6 inches on center. The underdrain must be encased in a layer of clean, double washed No. 57 stone, with a minimum 2-inch cover over the top of the underdrain. The underdrain system must include a flow control to ensure that the reservoir layer drains slowly (within 36 to 48 hours).

The underdrain outlet can be fitted with a flow-reduction orifice within a weir or other easily inspected and maintained configuration in the downstream manhole as a means of regulating the storm water detention time. The minimum diameter of any orifice is 1 inch. The designer should verify that the volume will draw down completely within 36 to 48 hours.

On infiltration designs, an underdrain(s) can be installed and capped at the downstream structure as an option for future use if maintenance observations indicate a reduction in the soil permeability. All permeable pavement practices must include observation wells. The observation well is used to observe the rate of drawdown within the reservoir layer following a storm event and to facilitate periodic inspection and maintenance. The observation well should consist of a well-anchored, perforated 4 to 6 inch diameter PVC pipe that is tied into any ‘T’ section or ‘Y’ section in the underdrain system. The well should extend vertically to the bottom of the reservoir layer and extend upwards to be flush with the surface (or just under pavers) with a lockable cap.

3.6.6. Infiltration sump (optional, required for underdrained Enhanced Designs).

For unlined permeable pavement systems, an optional upturned elbow or elevated underdrain configuration can be used to promote greater retention for permeable pavement located on marginal soils (see Figure. 17). The infiltration sump must be installed to create a storage layer below the underdrain or upturned elbow invert. The depth of this layer must be sized so that the design storm can infiltrate into the sub soils in a 48-hour period. The bottom of the infiltration sump must be at least 2 feet above the seasonally high water table. The inclusion of an infiltration sump is not permitted for designs with an impermeable liner. In fill soil locations, geotechnical investigations are required to determine if the use of an infiltration sump is permissible. In order to improve the infiltration rate of the sump, it may be designed as a series of 1-foot wide trenches spread 5 feet apart, which are excavated after compaction of the existing soils is performed. Excavation of these trenches may allow access to less compacted, higher permeability soils and improve the effectiveness of the infiltration sump (Brown and Hunt, 2009). Regardless of the infiltration sump design, the infiltration rate must be field verified.

3.6.7. Filter layer (optional).

To protect the bottom of the reservoir layer from intrusion by underlying soils, a filter layer can be used. The underlying native soils should be separated from the stone reservoir by a 2 to 4 inch layer of choker stone. The underlying native soils should be separated from the stone reservoir


As discussed in the above section 1.7, Geotextile fabric is (see Figure. 18) another option to protect the bottom of the reservoir layer from intrusion by underlying soils, although some practitioners recommend avoiding the use of fabric beneath permeable pavements since it may become a future plane of clogging within the system. Geotextile fabric is still recommended to protect the excavated sides of the reservoir layer, in order to prevent soil piping.

3.6.9. Impermeable Liner.

An impermeable liner is not typically required, although it may be utilized in fill applications where
 deemed necessary by a geotechnical investigation, on sites with contaminated soils, or on the sides of the practice to protect adjacent structures from seepage. Use a 30-mil (minimum) PVC geomembrane liner. Field seams must be sealed according to the liner manufacturer’s specifications. A minimum 6-inch overlap of material is required at all seams.

3.6.10. Materials Specifications.

Permeable pavement material specifications vary according to the specific pavement product selected.

3.6.11. Permeable Pavement Sizing.

The thickness of the reservoir layer is determined by both a structural and hydraulic design analysis. The reservoir layer serves to retain storm water and also supports the design traffic loads for the pavement. Permeable pavement structural and hydraulic sizing criteria are discussed below.

From the above different parameters the design of permeable pavement is executed.

4. Maintenance of permeable pavements

Maintenance is a required and crucial element to ensure the long-term performance of permeable pavement. The most frequently cited maintenance problem is surface clogging caused by organic matter and sediment. Periodic street sweeping will remove accumulated sediment and help prevent clogging; however, it is also critical to ensure that surrounding land areas remain stabilized.

The following tasks must be avoided on all permeable pavements:

- Sanding
- Re-sealing
- Re-surfacing
- Power washing
- Storage of snow piles containing sand
- Storage of mulch or soil materials
- Construction staging on unprotected pavement

Regular maintenance is recommended for permeable pavements. This may include re-sodding, laying gravel, and other small repairs. More typically, maintenance of a permeable structure refers to vacuum sweeping, pressure washing, or air blowing to remove debris. Vacuuming is recommended. (Pennsylvania Storm water Management Manual, 2005) Depending on the site, this may need to happen 2-4 times a year.

Concerns for maintaining the permeable pavement are typically limited to aesthetics and the prevention/repair of clogging. Proper design may prevent clogging, such as designing for drainage away from the porous section of pavement. This will keep debris from sweeping onto the pavement while allowing rain to infiltrate the soil below.


**Prevent Clogging of Pavement Surface with Sediment**
- Vacuum pavement twice per year
- Maintain planted areas adjacent to pavement
- Immediately clean any soil deposited on pavement
- Do not allow construction staging, soil/mulch storage, etc. on unprotected pavement surface
- Clean inlets draining to the subsurface bed twice per year

**Snow/Ice Removal**
- Porous pavement systems generally perform better and require less treatment than standard pavements
- Do not apply abrasives such as sand or cinders on or adjacent to porous pavement
- Snow plowing is fine but should be done carefully (i.e. set the blade slightly higher than usual)
- Salt application is acceptable, although more environmentally-benign deicers are preferable

**Repairs**
- Surface should never be seal-coated
- Damaged areas less than 50 sq. ft. can be patched with porous or standard asphalt
- Larger areas should be patched with an approved porous asphalt

4.2. Winter Maintenance

Winter maintenance for permeable pavements is simpler than that for typical pavements. Avoid using any abrasives, such as sand, on or near the porous pavement. Heat retention in the stone bed beneath the pavement tends to provide good snow melt, leading to reduced snow and ice problems. Snow plowing may be used with caution, setting the blade about an inch higher than normal. Salt may be used, however, nontoxic organic deicers are preferred, as the contaminated water will go directly to the water table.

**Repairs**

Drainage structure repair has the highest priority, in order to keep the system working as designed. Pavement structural repairs will be limited primarily to areas that have settled over soft soils. These areas may be patched with standard or permeable pavement. Potholes will rarely be a problem, due to the lack of a freeze-thaw cycle as in typical pavements. Seal coats ought not to be used,
as they would nullify the benefit of a permeable pavement.

Table 3. Maintenance schedule

<table>
<thead>
<tr>
<th>TIMING</th>
<th>COMPONENT</th>
<th>ACTION</th>
</tr>
</thead>
<tbody>
<tr>
<td>After storms</td>
<td>Gravel basecourse</td>
<td>1. Inspect paving area to check water drains away after heavy rain. Ponding may be due to clogging in drainage system.</td>
</tr>
<tr>
<td></td>
<td>Inspection chambers (if included)</td>
<td>2. Place in permeable paving to monitor water levels in base course.</td>
</tr>
<tr>
<td>Ongoing</td>
<td>Permeable paving</td>
<td>3. Where areas of paving settle, lift blocks, re-level bedding material and lay blocks at new level.</td>
</tr>
<tr>
<td>Monthly</td>
<td>Permeable paving</td>
<td>4. If present, mow grass and rescue as required.</td>
</tr>
<tr>
<td>Annually</td>
<td>Permeable paving</td>
<td>5. Sweep solid block or porous pavers with wet vacuum sweeper to prevent clogging with sediment.</td>
</tr>
<tr>
<td></td>
<td>Joint and bedding material</td>
<td>6. After cleaning solid block or porous pavers, check joint material and tap up as necessary.</td>
</tr>
</tbody>
</table>

5. Water quality

5.1. Pollutants

Pollution which presents on the road and car park surfaces as a result of oil and fuel leaks, and drips, tyre wear, and dust from the atmosphere. This type of pollution arises from a wide variety of sources and is spread throughout an urban area also known as diffuse pollution. Rainwater washes the pollutants off the surfaces.

Conventional drainage systems, as well as attenuation tanks, effectively concentrate pollutants, which are flushed directly into the drainage system during rainfall and then into watercourses or groundwater. The impact of this is to reduce the environmental quality of watercourses.

Impervious surfaces have a high potential for introducing pollution to watercourses. Possible water quality variables of concern include the following as stated in D’Arcy et al. (1998) and NCDENR (2005):

- Sediment and suspended solids (including phosphorus and some metals);
- Organic waste with high biochemical oxygen demand;
- Dissolved nutrients and pollutants (including nitrogen, heavy metals, solvents, herbicides and pesticides);
- Oil and grease; and faecal pathogens.

Five processes that affect the concentration of pollutants in the soil’s unsaturated zone:
1. Sorption,
2. Filtration,
3. Degradation,
4. Volatilization, and
5. Water transport.

Sorption tends to be the dominant process, and most pollutants will either be sorbed to soil particles or to organic matter. Storm water pollutants can also be adsorbed onto surrounding sediments in the storm water before they infiltrate into the soil. Mikkelsen et al. (1994) compiled research data showing that approximately 50 percent of the heavy metal load in storm water could be removed through either sedimentation or filtration.

Permeable pavements have a good track record at removing suspended solids and nitrogen. However, PPS, which do not rely on below ground infiltration and the use of an underdrain system, will not be successful in the removal of nitrogen. When an underdrain system is incorporated into the pavement design, storm water tends not to infiltrate into the soil, but into the underdrain, where it can be denitrified or removed by plant uptake (NCDENR, 2005).

Dierkes et al. (2002) summarised possible ranges of pollutant concentrations in rain, and roof and road runoff, taken from more than 60 sites throughout Europe. Rain may contain 5-day biochemical oxygen demand (1–2 mg/l), sulphate (0.56–14.40 mg/l), chloride (0.2–5.2 mg/l), ammonia (0.1–2.0 mg/l), nitrate (0.1–7.4 mg/l), and total phosphate (0.01–0.19 mg/l), copper (1–355 mg/l) and zinc (5–235 mg/l).

Another laboratory study by Fach and Geiger (2005) examined pollution removal rates of Cd, Zn, Pb, and Cu for permeable concrete block paving and three variations of concrete block pavers; one with wide infiltration pores (29mm), another with narrow pores (3mm), and pavers with a crushed brick substrate infill. Permeable concrete have the highest heavy metal removal rate (96.5% average) followed by block paving with brick substrate infill (92.9% average). No significant differences between the narrow infiltration pores and the wide pores were observed (63.1% and 78.6% average removal rates, respectively). When set over a 4 cm crushed basalt or brick substrate roadbed and a 40 cm limestone base course, average pollution removal rates for all pavements and substructures were very high, ranging from 96 to 99.8 percent.
5.2. Hydrocarbons

Oil and diesel fuel contamination is frequently detected on asphalt and other non-permeable surfaces. In comparison, these contaminants were not detected on PPS surfaces assessed by Bratterbo and Booth. Hydrocarbons can endanger soil and groundwater, if they are not removed sufficiently during infiltration through the surface layer. Many pollutants such as polycyclic aromatic hydrocarbons, metals, phosphorous and organic compounds are absorbed onto suspended solids. Models have been designed to estimate the suspended solids load and its dynamics during rainfall events, leading to better understanding of receiving waters being polluted by hydrocarbons.

Concerning various pavement systems, Booth showed that infiltrated water had significantly lower levels of copper and zinc in comparison to the direct surface runoff from the asphalt area. Motor oil was detected in 89% of samples from the asphalt runoff, but not in any outflow water sample from the PPS. Diesel fuel was not detected in any sample. Infiltrate measured five years earlier displayed significantly higher concentrations of zinc, and significantly lower concentrations of copper and lead.

Permeable pavements can operate as efficient hydrocarbon traps and powerful in-situ bioreactors. Coupe et al. found out that a PPS specifically inoculated with hydrocarbon-degrading microorganisms does not successfully retain a viable population of organisms for the purpose of increased hydrocarbon degradation over many years. Naturally developed microbial communities (i.e. no inoculation with allochthonous microorganisms) degrade oil successfully.

For the successful biodegradation of polycyclic aromatic hydrocarbons, certain environmental conditions need to be met. Degradation takes place when prolonged aerobic, sulphate reducing and denitrifying conditions occur. Very large hydrocarbon spills can be contained due to absorption processes within the pavement. Wilson incorporated an oil interceptor into a porous surface construction. Tests were carried out for worst-case scenarios such as the worst possible combined pollution and rainfall event to assess how the system retains pollutants within its structure. The results successfully demonstrated that this system can retain hydrocarbons, and can therefore offer outflow with improved water quality. However, where certain detergents are present in the pavement system, they can cause contamination of the outflow water, which may require secondary treatment to improve its water quality.

5.3. Metals

Studies have shown an improvement of water quality by filtration through PPS, which work well in removing suspended solids and particularly heavy metals from runoff. For example, Legret showed that suspended solids and lead can be reduced by PPS up to 64% and 79%, respectively. Kellem showed that enhanced filtration using organic media was an effective alternative to chemical precipitation for the treatment of storm water. Filtration through a specific adsorbent organic medium can remove about 95% of dissolved copper and zinc.

In comparison to pavements made of asphalt, concentrations of zinc, copper and lead were significantly lower on permeable structures. Lead concentrations were in fact undetectable. A PPS should regularly be kept clean to prevent clogging.

Generally, PPS are efficient in trapping dissolved heavy metals in surface runoff. However, not all pavers and joint fillings have the ability to trap dissolved heavy metals. Pavements with large joints for infiltration must have a suitable joint filling. Otherwise, metals will pass through them, and may subsequently enter groundwater resources. Particles usually accumulate in geotextiles and on pavement surfaces. Geotextiles usually separate micro pollutants such as cadmium, zinc and copper from the underlying soil, therefore preventing groundwater from becoming contaminated.

5.4. Microbiology

PPS are powerful in-situ bioreactors, which can reduce hydrocarbon contamination by 98.7%. Biodegradation in PPS is enhanced by bacteria and fungi. When inoculated with microorganisms, the protozoan population diversity within a PPS increases more rapidly than in a similar non-inoculated system. Pavements contain testate amoebes, ciliates, flagellates and gym amoebae. The understanding of microbial biodiversity helps to interpret biodegradation mechanisms.

PPS have the capacity to degrade large quantities of clean motor oil. Bio-treat HD, a commercially available oil degrading microbial mixture, will not degrade oil any better that the local microbial biomass established within the pavement over a long period of time. However, the local microbial biomass can only achieve high degradation rates, if there is adequate supply of nutrients (i.e. nitrogen and phosphorous) in the feed. Monitoring of biofilm development through scanning electron microscopy has revealed that a PPS can obtain a high degree of biodiversity due to the development of complex microbial compositions.

The assessment of the microbiological water quality has been an important process in preventing waterborne diseases. The two most common alternate tests carried out are for coliforms and Escherichia coli, or faecal coliforms. Total coliforms, faecal coliforms, faecal streptococci, heterotrophs, fungi, Pseudomonas aeruginosa, Leptospira, salmonellae and viruses are often analysed in an attempt to determine the temporal distribution of bacterial pathogens and viruses in storm water runoff. However, findings usually show that it is not possible to accurately predict the time when peak
microbial populations including human pathogens occur in runoff waters.

5. Recent research works.

5.1. Combined Geothermal Heating and Cooling effect

The technology has many names: ground source heat pump (GSHP), ground coupled heat pump (GCHP), geothermal heat pump (GHP), geo-exchange (GX), Earth energy system.

5.1.1. Introduction to Geothermal Heat Pumps.

Geothermal heat pumps (GHP) or geo exchange systems are commonly used in North America, China, Japan and some European countries. Most GSHP use refrigerant to move unwanted energy (i.e. heat) out of buildings during summer and into them (if required) during winter. (Bose JE. (2005)) They use constant temperatures of surrounding grounds, which are lower than the corresponding air temperatures during warm seasons (heat sinks) and higher during cold seasons (heat sources). For ground connections, plastic pipes are installed within the soil. Various applications such as horizontal, vertical, looped or submerged designs can be used. The main thermal carrier within coils is a mixture of water and a de-icing agent. The length and width of the loops is determined by ground conductivity abilities. The most important variables are type of soil, geology and area of available land for such installations.

5.1.2. Health risks associated with permeable pavement systems.

Various applications of PPS have been tested in the UK. The main pollutant used was mineral engine oils containing hydrocarbons. Furthermore, a specific geotextile incorporating polymer beads was designed to release nutrients for better microbial community growth and more efficient hydrocarbon removal. Spicer GE et al. (2006) this ‘self-fertilising’ geotextile demonstrates that nutrient sources can be incorporated into a polymer composite to influence positively microbial growth within PPS.

A different approach has been taken at ‘The University of Edinburgh’. The research team had decided to use gully pot liquor mixed with tap water and animal faeces in some experimental rigs as the main pollutants. Such mixtures would mimic the most extreme conditions that may occur in practice. Gully pot liquor provides all possible pollutants available naturally. A gully pot is a biochemical reactor where pollutants are released after acidic dissolution and sediment maturation. Also various microbial degradation processes take place in the gully pot chamber. Morrison GM et al. (1995) because gully pots operate under various regimes (e.g. wet or dry), concentrations of dissolved oxygen can drop rapidly during anaerobic conditions. Butler D et al. (1995) Because of their potential pathogenic nature, animal faeces (e.g. dog droppings) are not commonly used pollutants in academic SUDS research. Nevertheless, there are serious health concerns associated with PPS water (particularly if contaminated with faecal matter), which could potentially be recycled within buildings for toilet flushing and other applications as discussed by the authors previously (Grabowiecki P et al. (2006)).

Both PPS and GSHP are commercially available applications, but were never used as combined systems in a research project. A combined system has the potential to capture, detain and treat runoff, and to either cool or heat a nearby building at the same time. The sub-base is only heated passively during the summer when hot air within an adjacent building needs to be cooled down by transferring access heat to below the permeable pavement. The heat is in fact a waste product that has the additional benefit of enhancing biodegradation within the sub-base. The rationale is to assess the impact of temperature changes induced by the geothermal heating and cooling system on the water quality.

5.1.3. Integration of PPS with Geothermal Heat Pumps

Environment not only prevents and reduces the risk of flooding and pollution of watercourses, but also reduces energy costs by the application of a green energy source (earth energy) which adds many other environmental benefits (Scholz and Graboweicki, 2008). Permeable pavement engineering is an effective and simple method of providing structural pavements whilst allowing storm water to infiltrate freely through the surfaces for temporary storage, storm attenuation, dispersal and reuse. Permeable pavement systems (PPS) are a sustainable urban drainage system (SUDS) whereby water from urban runoff can be treated by filtration and sedimentation for recycling, harvesting or reuse purposes. Geothermal Heat Pumps (GHPs) also referred to as ground source heat pumps are
receiving increasing interest because of its potential to reduce primary energy consumption, reduce emissions of greenhouse gases and thus reduce the effects of climate change (Tota-Maharaj et al., 2009).

5.2. Water recycling using permeable paving

The physical attenuation of storm water pollutants by permeable pavements with varying designs of geotextile membranes. The research would give an indication as to the effects of contaminants present in urban runoff and the possibility of biodegradation by anaerobic processes occurs. One of the guiding principles of SUDS is centred on mitigating adverse effects of urban storm water runoff such as increased urban flooding and deteriorating receiving water quality. SUDS such as permeable pavements are commonly perceived as an effective source control measure to reduce storm water flows and pollution loads. However, there have only been limited studies aimed specifically at quantifying the effectiveness of utilising permeable pavements as a source control measure.

The recycling and reuse of rainwater, using permeable paving as the reservoir for storage, shows great potential in the reduction of mains water use for low grade uses. Water for toilet flushing, landscaping and car washing can be stored in the pavement structure and pumped out for reuse.

5.2.1. Rainwater harvesting after storage in permeable pavements

Permeable pavements built to the Hanson Form pave specification have an average storage capacity of around $1 \text{m}^3$ per $10 \text{m}^2$ of paving with an excavation depth of 500 mm. This storage capacity is easily realised by the provision of a lining system, usually based on a Visqueen-type material. Once the build is complete, accessories such as electric pumps can be added in order to move the water into the house for WC flushing or for external use such as landscaping.

The onsite use of rainwater for non-potable purposes in both domestic and industrial settings shows great promise in reducing the need for highly purified mains water. In a domestic setting at certain times of the year, over 50% of water could be supplied by the use of rainwater, certainly when feeding sprinkler systems in dry weather. The use of a permeable pavement as the storage element in rainwater harvesting makes efficient use of a large potential storage volume, adheres to SUDS principles and value engineering good practice, realising significant savings for the end user.

5.2.2. Contamination of stored rainwater

When rainwater falls onto an urban receiving surface, whether that surface is a roof, road, pavement or car, it usually becomes contaminated relative to the water quality of the original rainfall. This is because rainfall is relatively free of contaminants except for materials like pollen, microbial spores, very fine dust and sometimes dissolved gases such as SO2 and NO2. After falling and coming into contact with surfaces, non-permeable urban surfaces tend to have any pollutants on them scoured off by the rainfall and moved, sometimes quite a large distance from their origin (Charlesworth et al, 2003).

If rainwater is to be harvested for later use then there are many measures available to remove the larger contaminating waterborne fractions; these include filters, screens or grit traps. These measures are very effective in preventing blockages of pipework, but do not remove most of the smaller particles which may find their way into the storage reservoir. These smaller sized fractions include microorganisms typically between 2 and 20 micrometres in size.

5.2.3. Microbiological contamination of harvested rainwater

When rainwater falls onto an urban receiving surface, whether that surface is a roof, road, pavement or car, it usually becomes contaminated relative to the water quality of the original rainfall. This is because rainfall is relatively free of contaminants except for materials like pollen, microbial spores, very fine dust and sometimes dissolved gases such as SO2 and NO2. After falling and coming into contact with surfaces, non-permeable urban surfaces tend to have any pollutants on them scoured off by the rainfall and moved, sometimes quite a large distance from their origin (Charlesworth et al, 2003).

If rainwater is to be harvested for later use then there are many measures available to remove the larger contaminating waterborne fractions; these include filters, screens or grit traps. These measures are very effective in preventing blockages of pipework, but do not remove most of the smaller particles which may find their way into the storage reservoir. These smaller sized fractions include microorganisms typically between 2 and 20 micrometres in size.
Any microbiological contamination in water harvesting schemes would come primarily from animal wastes from cats, dogs, rodents or birds. The unpredictability of any such contamination episodes is one of the reasons why such phenomena are difficult to study. It is clear that at times the number of potentially harmful microbes in urban water, e.g. faecal coliforms, is high (Ferguson et al, 1996; Butler and Davies, 2000). Potentially there are a number of possible contaminating microbial types in harvested rainwater, of different taxonomic descriptions (Evans et al, 2006; Grabiowiecki et al, 2008) and which may increase in number under a variety of different conditions. It should be noted that most of the organisms would come from animal faeces and this represents the most likely contamination of the stored water. Since there is no definitive data on the microbiological safety of rainwater harvesting systems, many harvesting systems have a microfilter which would remove most bacteria and protists from the system. Such filter systems are relatively susceptible to faults such as blockages if a large amount of suspended material is in the water, for example after intense rainfall.

UV light sterilisation kits are also available that would remove the vast majority of micro-organism from the water, although these are relatively expensive to install and also require some maintenance. However, in general, a properly designed, installed, monitored and maintained harvesting system should provide excellent water saving benefits with little risk to the user.

Despite these safeguards, from an information gathering perspective and also to simulate a ‘worst case’ scenario, it was decided to apply two selected microbial contaminants from the above list to a simulated permeable paving system to determine the density of these microbes within the paving system after contact with the Aqua flow geotextile, Inbitex. Inbitex is known to very effectively filter out chemical and particulate pollutants from water (Newman et al, 2002). The interactions between the contaminants and the indigenous microbial population of the paving system were also of considerable interest to reduce the microbial effects on the urban runoff.

5.2.4. Innovations and Future Research

To date, the application of permeable pavement systems has been limited to roadways for vehicular travel. Ongoing and future research could potentially allow for new and innovative applications such as with airport runways. There is a myriad of different applications where human’s quest for development is hindered by environmental consequences. It is possible that with the use of permeable pavements these events may not be so catastrophic. Landslides are one example. Until recently, landslides were only thought to be associated with high intensity rainstorms on steep inclines. However, recent studies have shown that the threshold of rainfall intensity versus duration for shallow sloped landslides to occur is lower than previous estimates (Guzzetti, E. et al. 2007).

It was found that the rainfall intensity plays a more important role in increasing the chances for landslides to occur due to the sheer quantity of water draining over a short amount of time (Guzzetti, E. et al. 2007). These conditions can be exasperated by human development, which alters the drainage path of the rainwater, increasing the likelihood of a landslide (Ozdemir, A et al. 2008). This is where the permeable pavement design could come into play.

Virtually all the studies conducted on permeable pavement have noted its incredible hydrological properties; because the permeable pavement allows water to pass through it in to the soil it does not significantly alter the drainage path of the rainwater. This means that structures could potentially be built with a permeable foundation. So, they would have little impact on the surrounding environment.

The research focuses also on improving the growth of microorganisms during artificial temperature fluctuations induced by the heat pump.

Further research on the short and long-term effects of contaminants that remain in the PPS should be undertaken. The self-sustainability of these relatively new systems in comparison to traditional pavements requires further assessment. Moreover, the long-term impact of PPS on the environment is still unclear.

Before all of this can be accomplished though more research has to be put into improving the lifespan as well as decreasing the costs of permeable pavement. Hopefully if these two negative aspects of permeable pavement can be eliminated these systems can be installed in more places around the world.

6. Conclusions

This paper looked at various studies conducted on permeable pavement systems and their current application. Also discussed about the detailed design of permeable interlocking concrete pavement in brief. Maintenance and water quality control aspects relevant to the practitioner were outlined for permeable pavement systems. The water quality aspects is highlighted. Recent innovations were highlighted and explained, and their potential for further research work was outlined. The recent innovations like development of a combined geothermal heating and cooling, water treatment and recycling pavement system is promising and it is detailed in cut short, future research works are outlined in brief. These permeable pavement systems are changing the way human development interacts with the natural environment. Its application towards parking lots, highways and even airport runways are all improvements in terms of water quality, water quantity and safety.
References


